Simulating "Fog-of-War" in Military Decision-Making

Pat Talbot
Joint National Test Facility
730 Irwin Avenue, Room 270
Schriever Air Force Base, CO 80912-7300
pat.talbot@jntf.osd.mil

ABSTRACT: *The Joint National Test Facility at Schriever AFB is developing a next generation command and control simulation for analyzing future ballistic missile and air defense systems. An important component of this simulation is the representation of a realistic, automated decision-making process, the "Simulated Commander." This paper describes our work toward coping with a particularly difficult requirement: simulate the effects of "Fog-of-War" on decision-making. This is defined as the influence of real-world uncertainties, conflicts in information, and attention deficits that degrade human decision-making. Our approach to representing and reasoning in the presence of fog-of-war is to apply perturbations to the input, processing, and output of various reasoning algorithms to appropriately insert a variety of its effects. These include lost inputs, latencies, modified priorities, degraded confidence, operator confusion, and misplaced outputs. The module has been formulated to allow selectable "fog settings". A test bed was constructed to prototype a "thinker" module, a missile launch scenario, and related decision-making. A graphic user interface has been implemented and connected to a Dempster-Shafer Belief Network for data fusion. Results to date are intuitively satisfying; e.g., it does appear that perturbations to a probabilistic belief network credibly mimic fog-of-war effects on decision-making.*

1. Introduction

The Joint National Test Facility (JNTF) is the arm of America's Ballistic Missile Defense Organization (BMDO) dedicated to ensuring the integration, interoperability, and effectiveness of America's missile and air defense systems. The JNTF provides expert Modeling and Simulation (M&S), analysis, testing, wargaming, and exercise support to the Department of Defense (DoD), joint, individual service, and international acquisition and war fighting communities. Several of these objectives will be met with the development of new joint service multilevel real-time wargame simulation called Wargame 2000 (WG2K). In the conduct of WG2K, a considerable number of players are required, and many travel to the JNTF from distant locations. Allowing the "players" to participate from their home locations by using remote terminals and established communication nets substitutes human travel for purchased hardware and communications costs. In some situations, this is cost effective; however, many people are still required to devote considerable time in every wargame that we conduct. This is especially true if the wargame is focused on some particular role, then the other "players" are needed to keep the test realistic but benefit little from participating. Selectively replacing human participants with Simulated Commanders is an approach that is intended to minimize monetary and human costs while still providing realistic “players” for a wide range of wargame functions.

WG2K has requirements for fully automated command decision-makers that realistically represent human commanders at any level in the command hierarchy of a joint services Ballistic Missile Defense (BMD) wargame. An important component of this simulation is a realistic automated command decision-making process, or a “Simulated Commander.” This paper provides a conceptual design for coping with a particularly difficult requirement: simulate the effects of "Fog-of-War" on decision-making. This is defined as the influence of real-world uncertainties, conflicts in information, and attention deficits that degrade human decision-making. Our approach to representing and reasoning in the presence of fog-of-war is to apply perturbations to the input, processing, and output of various reasoning algorithms to appropriately insert a variety of its effects. These include lost inputs, latencies, modified priorities, degraded confidence, misattribution of evidence, and misplaced outputs. The module has been formulated to allow selectable "fog settings". A test bed has been constructed to prototype this "thinker" module using a missile launch scenario, and probabilistic decision-making for concreteness. Results to date are intuitively satisfying - it does appear that perturbations to a probabilistic belief network credibly mimics fog-of-war and it's effects on decision-making.

2. Approach

The overarching approach to demonstrating fog-of-war in simulated commander decision-making (Figure 1) consisted of defining causes and using operators to map them to effects on input, processing, and output. Causes were identified by a requirements analysis, identifying tools (decision algorithms) for testing the design, organizing sources of "fog", and factoring in uncertainty, unreliable of information, and human errors that make fog-of-war difficult to simulate. Causes were identified as pertaining either to the data, the human, or the computer processing. Effects were allocated to inputs, processing, and outputs of reasoning algorithms to foster universal applicability. The resulting "cause and effect matrix" was then applied using "operators" that quantified the effects. Significantly, causes are defined according to how often a perturbation occurs (frequency) and how intense the perturbation is (severity). For example, conflict is defined as belief in some data is decreased: "some" is quantified as the frequency of occurrence, and the value associated with "decreased" refers to the severity of the effect.

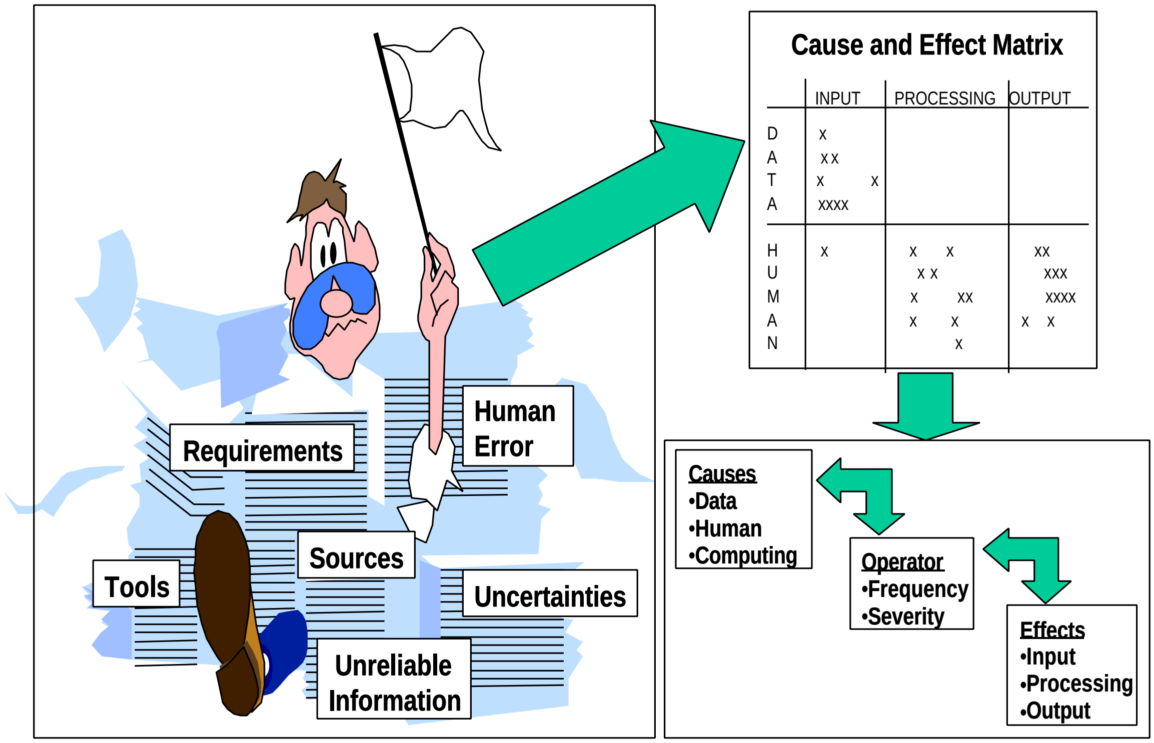


Figure 1 – Fog of War Approach

We derived requirements for simulating the fog-of-war from requirements (Figure 2) in the WK2G specification. The gleaned phrases are: ambiguity, disruption, timeliness, overload, indecision, confusion, stress, fear, stroke, fatigue, and unanticipated threats. These causes of "fog" were supplemented based on discussions with wargame developers to produce a more complete set of causes, both data-related, human, and processing-related.

From the Wargame 2000 System Software Specification, April 97:

R-031 The Wargame 2000 System shall be capable of supporting the simulation of the experience of "fog of war" in a wargame, which may include:

1. **Ambiguity in attack assessment**
2. **Disruption of critical data links and nodes connecting sensors to the BMC3 system**
3. **Exceptionally heavy weather effects such as flooding, blizzards, volcano, and heavy fog that reduced performance of sensor and battle management**
4. **Inability of key sensors and nodes to perform their mission during an enemy attack (for reasons such as sapper attack)**
5. **Inability to gain prosecution decisions from the NCA, alternates, or defined CINC in a timely manner**
6. **Insufficient bandwidth or extensive communications delay in intelligence traffic, including excess information causing overload, such as “rattle-around”**
7. **Indecision or confusion caused by battle related stress such as fear, stroke, fatigue**
8. **Unanticipated threats or countermeasures that degrade sensors, sources, and methods resulting in confusion in battle management command and control.**

Figure 2 – Fog-of-War Requirements

Because we anticipate many forms of reasoning to be performed by the Simulated Commander (heuristic, probabilistic, case-based, and possibly neural) causes of "fog" were defined based on their impact on inputs, processing, and outputs of reasoning algorithms (Figure 3). This has the added advantage of applying to other wargame objects subject to "fog-of-war"; namely, humans, weather, sensors, weapons, and communications.

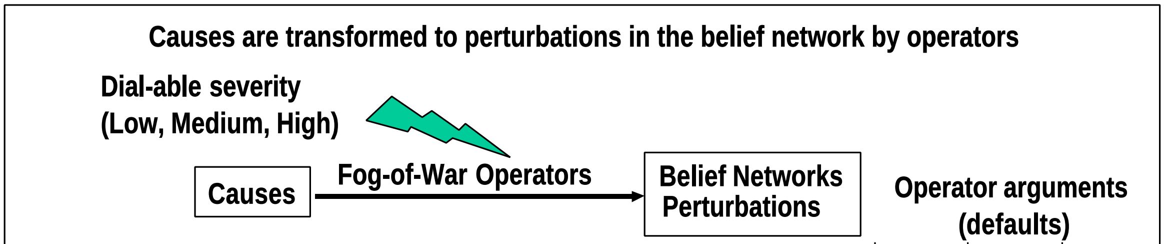
• Based on specified and derived requirements, a limited set of causes are defined based on their impact on inputs, processing and outputs

Loss : some input data is lost
Latency: some input data is delayed
Asynchrony: input data dispersion (standard deviation) is increased
Degradation: some input data is delayed and belief in it is decreased
Ambiguity: some data is mislabeled (generalized) and belief in it is decreased
Conflict: belief in some data is decreased
Overload: volume of some data is increased, with no impact on fusion results
Bad Luck: belief in some data is decreased (simulating “poor” Monte Carlo draws)
Surprises: belief in some data is decreased and some results are not transmitted
Disposition: some network weight decreased. Some decision thresholds are increased. Some outputs are not sent, delayed, or degraded in quality.
Cognition: some network weights or logical operators are modified. Some output is degraded.
Confusion: some network links are transposed or dropped.
Priorities: some outputs are delayed
Miscommunication: some network weights are modified, Some outputs are degraded.
Assumptions: some network weights are modified, some decision thresholds are increased, and some outputs are degraded.

Figure 3 - Definition of Causes

3. Results

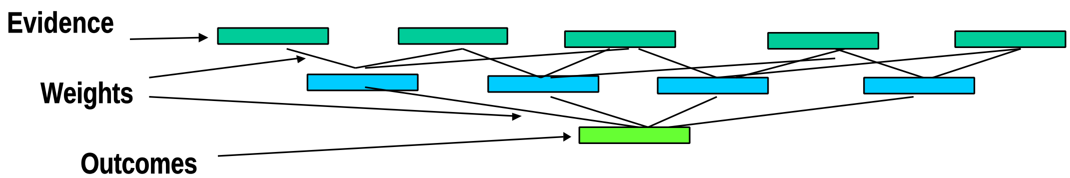
Formulation: Causes of fog-of-war that impact human decision-making were successfully derived from requirements and discussions with domain experts. These were mapped to effects on reasoning algorithms; specifically the Dempster-Shafer Belief Network, using simple "operators". A combination of operators was then defined to convert causes into effects (Figure 4). Also shown are default values for these operators corresponding to "low", "medium" and "high".



Operator	Abbr	Definition	Low	Med	High
Random	rnd	Compares uniform random number to threshold	.2	.4	.6
Delay	dt	Extends receipt & transmit time by a factor	1.33	1.66	2.0
Disperse	std	Increases standard deviation by a factor	.2	1.0	2.0
Degrade	db	Decreases input belief by a factor	.2	.4	.6
Mistype	oth	Generalizes input type for less impact	.2	.4	.6
Conflict	neg	Changes a fraction of positive input to negative	.2	.4	.6
Overload	ovr	Sends a factor more input, same result	.2	.4	6
Derate	wt	Decreases "THEN" or network weights by a factor	.2	.4	.6
Transmit	tx	Decrease number of results sent	.2	.4	.6
Disconnect	zer	Zeroes a fraction of AND/OR or network links	.2	.4	.6
Threshold	thr	Increase decision threshold by a fraction	.2	.4	.6

Figure 4 – Fog-of-War Operators

Each of these operators was defined for the first reasoning algorithm for which we attempted to apply this fog-of-war formulation - a Dempster-Shafer Belief Network for data fusion (Figure 5). We defined, via operators, data-related and human causes of perturbation to evidence (input), weights (processing), and outcomes (output) of a belief network. Typically, caused are related to effects by two operators; e.g., random (quantifies frequency of occurrence) and conflict (quantifies severity of the effect).



- Each cause can be modeled using a unique set of operators on a belief network

Causes	Evidence	Weights	Outcomes
Loss	random, drop		
Latency	random, delay		
Asynchrony	random, disperse		
Degradation	random, degrade		
Ambiguity	random, mistype		
Conflict	random, conflict		
Overload	random, overload		
Bad Luck	random, degrade		
Surprises	random, degrade		random, transmit
Disposition		random, derate	random, transmit
Cognition		random, derate	random, degrade
Confusion		random, disconnect	
Priorities			random, delay
Miscommunication		random, derate	random, drop
Assumptions		random, derate	random, threshold

Figure 5 – Belief Network Perturbation

The final step was to provide a graphic user interface and integrate this fog-of-war formulation into the existing simulated commander. The results obtained are reported in the next section.

Algorithm Integration: A major hurtle that we overcame was to show how already uncertain inputs to a reasoning algorithm (Dempster-Shafer Belief Network) could be perturbed by fog-of-war (Figure 6). Resources, such as a battle manager or intelligence terminal, provide evidence related to various hypotheses (e.g., was the foreign space launch hostile?). The information source, the Basic Probability Assignment (BPA) which specifies the degree of belief in the hypothesis, and the time of the input are collected. Here, we found that fog-of-war operators directly perturb one or more of these three parameters. The random operator is first employed to determine whether to apply a perturbation. If so, the source may be changed, the BPA may be decreased, or the time may be change, depending on the operator. After applying fog-of-war to the input, the fusion algorithm[i] proceeds in the regular way: a Cartesian product fuses the new evidence with previous evidence, normalization drops unsupported beliefs, belief and plausibility are computed, and results are plotted on a timeline.

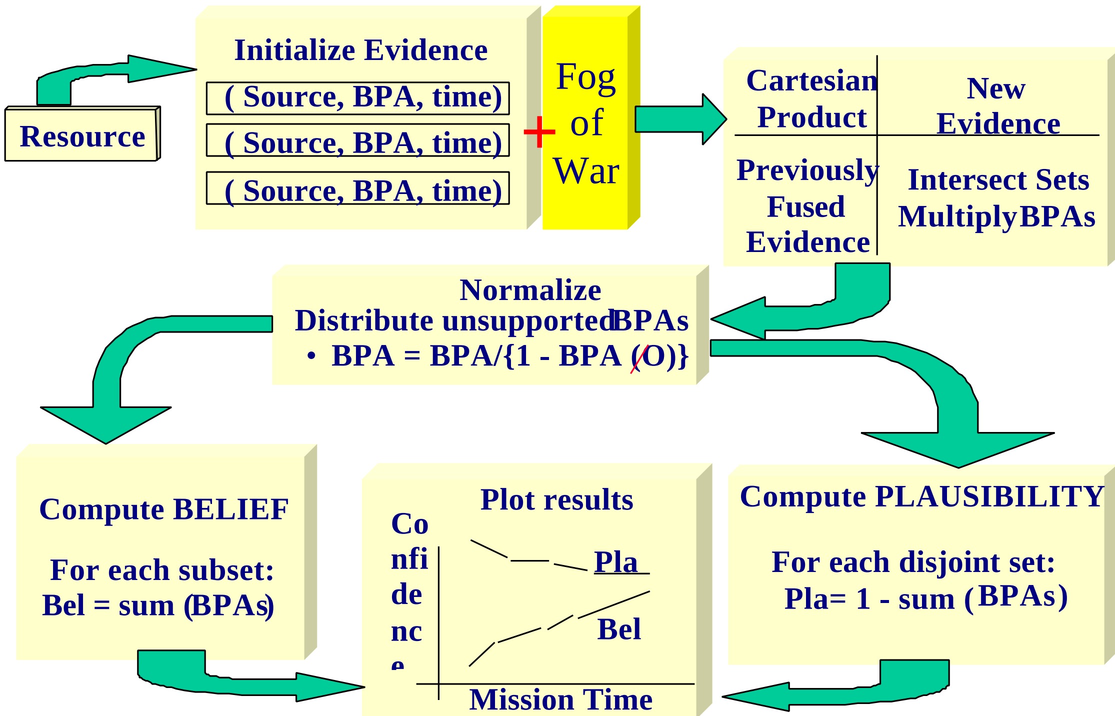


Figure 6 – Fog-of-War Using Dempster-Shafer

The belief network has three layers: evidence, indicators, and outcomes - that successively refine data. These are connected by links called "weights". We found that processing is easily perturbed by modifying the weights in the belief network. They may be modified in value, scrambled, or deleted - depending on the operator. Similarly, outputs may be delayed, degraded in quality, or not sent at all.

Processing: A more detailed view of the code that implements fog-of-war in a belief network (Figure 7) reveals the processing steps:

- Determine if fog-of-war is enabled
- Get "fog factors"
- Determine whether to apply
- Apply severity factor

In the example, the confidence in evidence is decreased due to a "loss".

```
#define FOG_EVIDENCE       0
#define FOG_WEIGHT         1
#define FOG_OUTCOME        2

#define FOG_LOSS           0
#define FOG_LATENCY        1
#define FOG_ASYNCH         2
#define FOG_DEGRADATION    3
#define FOG_AMBIGUITY      4
#define FOG_CONFLICT       5
#define FOG_OVERLOAD       6
#define FOG_BADLUCK        7
#define FOG_SURPRISE       10
#define FOG_DISPOSITION    11
#define FOG_COGNITION      12
#define FOG_CONFUSION      13
#define FOG_PRIORITIES     14
#define FOG_MISCOMM        15
#define FOG_ASSUMPTION     16
```

- **Use 'FOGenabled' to determine if Fog-of-War processing is enabled.**
- **Use 'FOGet' to determine if specified cause is enabled and to get Fog Factors.**
- **Use 'random' and first return value to determine if effect should be applied.**
- **Use second return value to perturb the system.**
- **Example below shows effect on EVIDENCE due to LOSS cause.**

```
if ( FOGenabled  () ) {
    if  ( FOGget (FOG_LOSS, FOG_EVIDENCE, fogfactors ) > 0)
            if (random() <=fogfactors [0])
                confidence = confidence – fogfactors  [1]*confidence;
    }
```

Figure 7 – Fog-of-War Application

Displays: A user interface was constructed using the XFORMS display builder (Figure 8). The "Fog of War Control" allows users to load, edit, and save settings. Defaults are modified by selecting data-related or human causes, or by selecting effects evidence, weights, or outcomes. Fog can be turned "on" or "off" globally in one click.

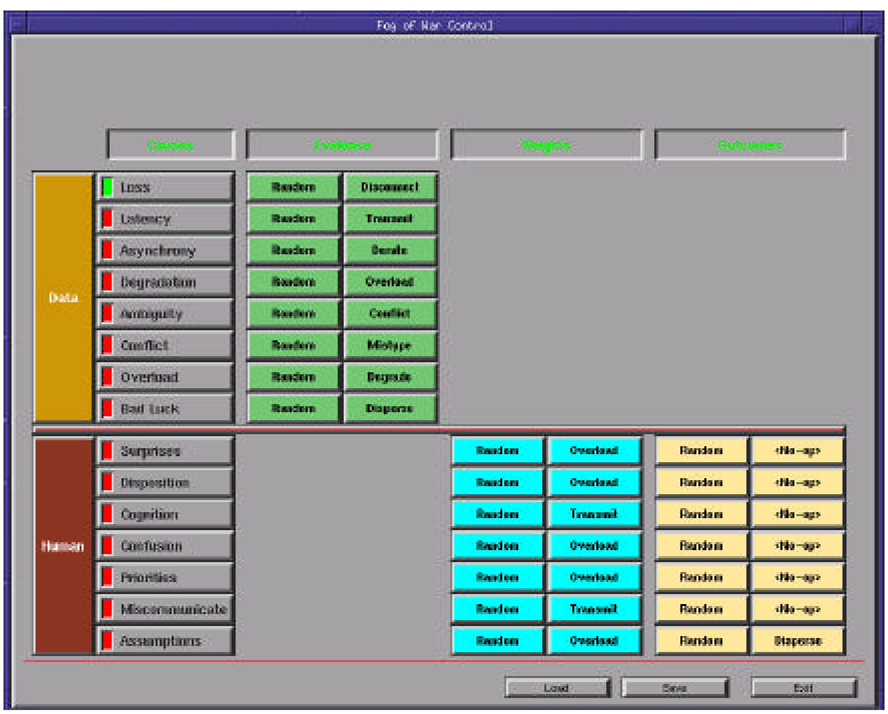


Figure 8 – Fog-of-War Control Display

Architecture: Having integrated fog-of-war with the belief network algorithm, the ensemble was then interfaced with our "Automated Decision Support System". This provides proof-of-concept for simulated commander functionality and for semi-automated decision support to human decision-makers (Figure 9).

The Simulated Commander Controller contains the fog-of-war control, a knowledge base, the Simulated Commander, Subagents, and decision support services. A "white" control, or simulation conductor, manages fog-of-war unknown to the simulated commander who only receives perceived data inputs from battle managers and an intelligence terminal. We have integrated these code modules and they work together.

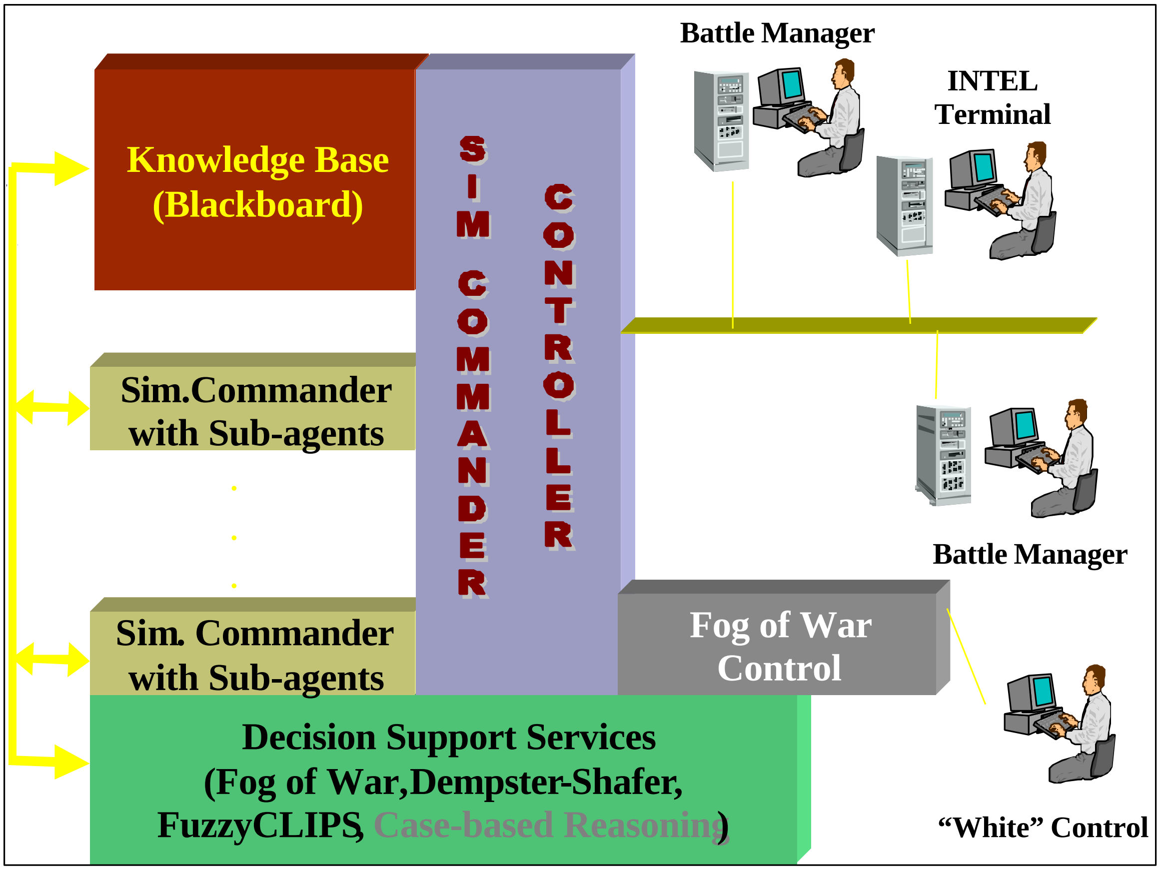


Figure 9 – Automated Decision Support System

The Simulation Control Console (Figure 10) is the summary display used by the Simulated Commander Controller - a member of the simulation conductor team. The console provides visibility into the behavior of Simulated Commanders, tracks algorithm and fog-of-war settings, shows evidence and history traces, and scores decision quality.

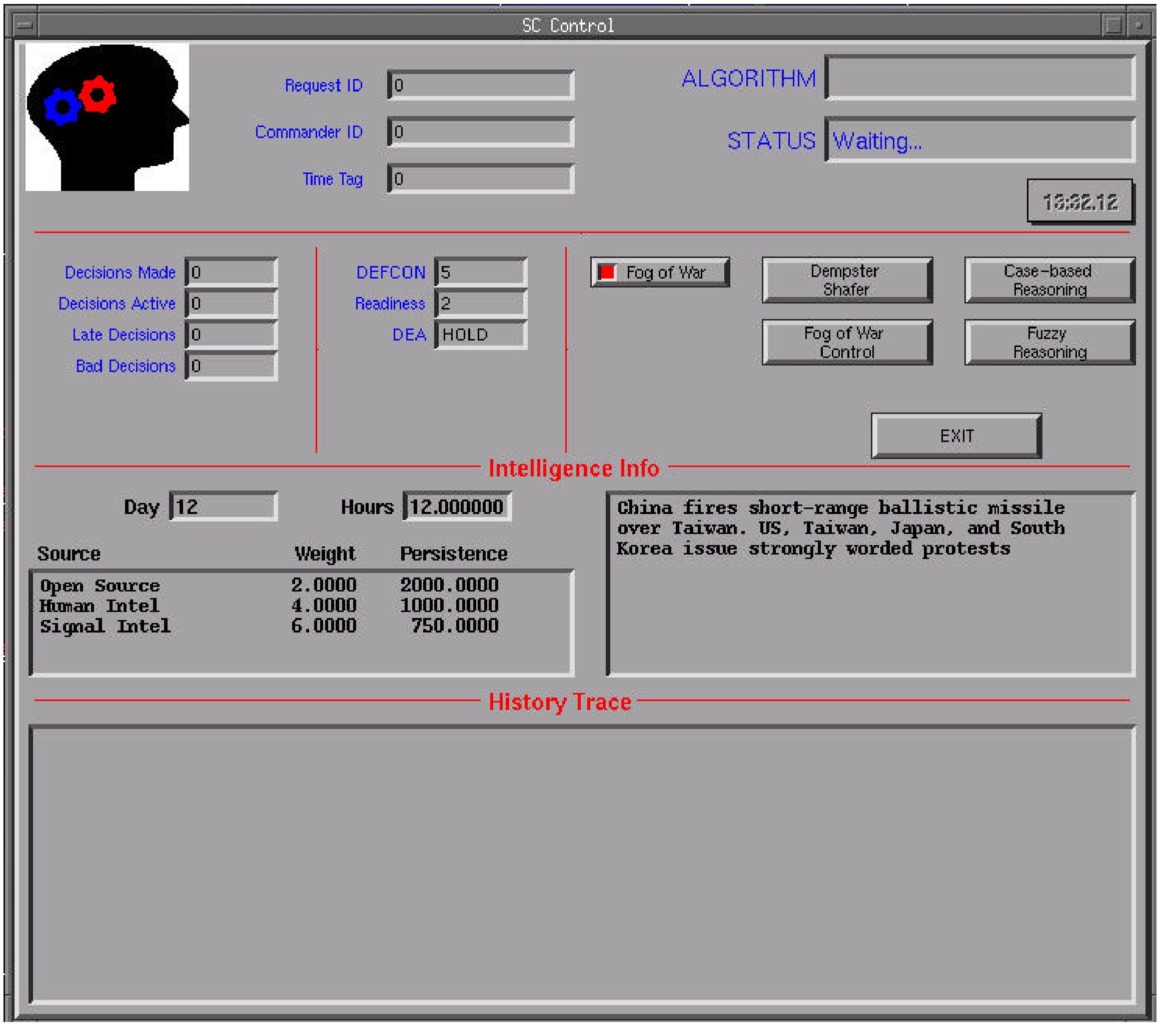


Figure 10 – SCC Simulation Control Console

Fog-of-War Example: The task of Foreign Launch Assessment (Figure 11) was chosen as a scenario to show how decision quality and timeliness are impacted by fog-of-war. Simply stated, the simulated commander must decide whether a particular missile launch is a deliberate, foreign, Intercontinental Ballistic Missile (ICBM) threat. Situation indicators and a map are shown. New data, which is uncertain, incomplete, and sometimes conflicting, is received. A timely Rule of Engagement (ROE) directive must be issued based on the new data. The decision process (lower right) is based on a Dempster-Shafer Belief Network which fused new data, forms indicators (ballistic, threat, valid), and produces as assessment based on this causal network.

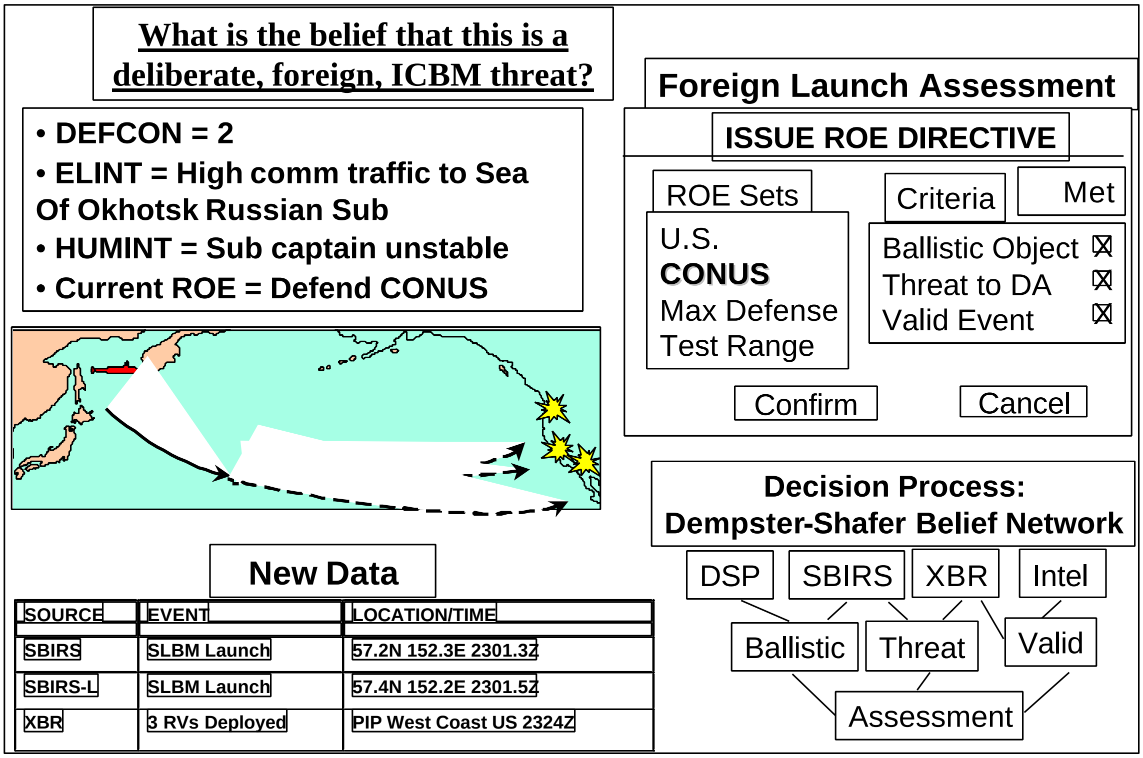


Figure 11 – Fog-of-War Example

Applying fog-of-war factors (Figure 12) has significant effects:

- Without fog, the decision threshold is reached in time: confidence in the assessment (upper right) that the threat is a hostile ICBM is above the threshold (horizontal dotted line) before the time deadline (vertical dotted line). The decision is successful.
- With fog, confidence in new data is lower and sufficient confidence in the assessment (lower right) does not occur in time. The decision is too late.

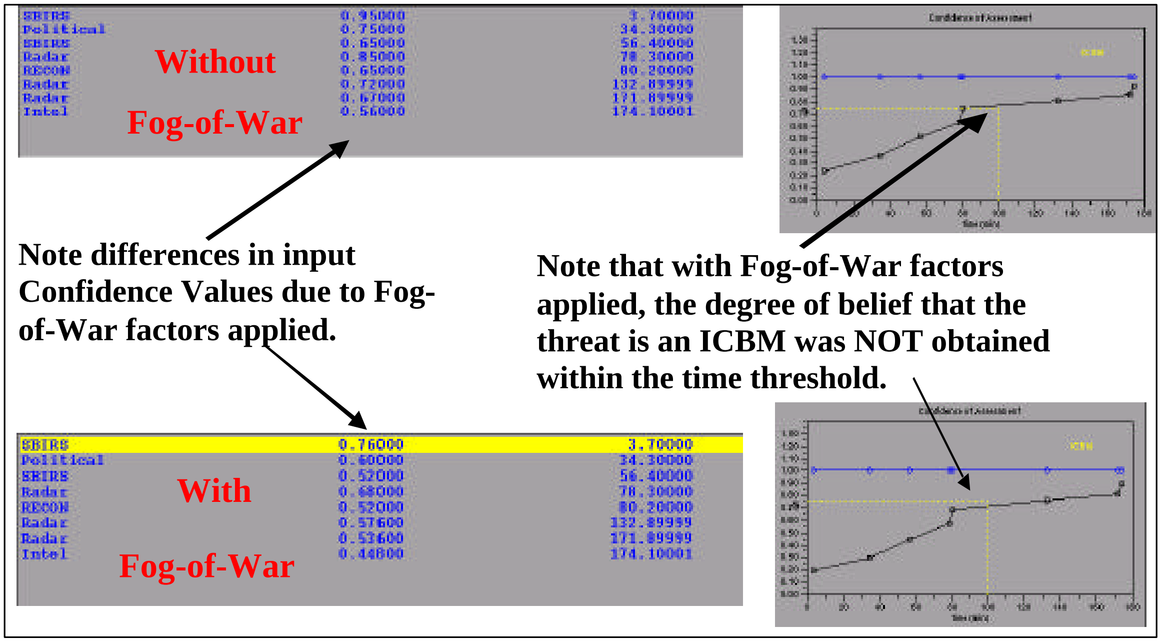


Figure 12 – Fog-of-War Example Results

4. Discussion

Summary: Work to date has focused on providing a proof-of-concept for adding fog-of-war to decision support. We have defined requirements, provided a scenario context, formulated a fog-of-war algorithm, produced a detailed technical approach, and applied the solution to a belief network.

Future Work: The "operator-based" solution will be applied to rule-based reasoning - we use Fuzzy CLIPS - for a Patriot Battalion Commander decision process. It will also be extended to a case-based reasoner for Patriot Battalion Commander planning process. Based on the observation that a little "fog" produces serious degradation in decision performance, metrics will be collected and default valued for operators will be modified to enhance realism.

Author Biography

Pat Talbot is a Delivery Order Lead of the Technology Insertion Studies and Analysis Delivery Order at the JNTF. He formulated the Fog-of-War concept described here and has overall responsibility for Simulated Commander work at the JNTF. Mr. Talbot has 27 years experience at TRW in missile defense analysis, software development, and project management. Education: BS Physics and Mathematics from Penn State, MS Physics from Penn State.

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[i] Stein, R., The Dempster-Shafer Theory of Evidential Reasoning, AI Expert, August 1998.